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Article

A Detailed Record of Deglacial and Early Post-Glacial Fluvial Evolution: The River Ure in North Yorkshire, UK

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Abstract: The lower reaches of the River Ure, on the flanks of the Pennine Hills in northern England, contain sedimentary and erosional landforms that are a record of fluvial activity during deglaciation and valley-glacier retreat at the end of the last (Devensian) glacial period, and in the subsequent post-glacial Holocene. Terraces and channels, most of which are now relict features well above the altitude of the present river, attest to the impacts of massive meltwater discharge and deposition of sand and gravel outwash, and dynamic river regimes with rapid incision. Through field survey, we have created a detailed geomorphological map of these landforms and glacial and fluvioglacial surface deposits, as well as the terraces and palaeochannels that were abandoned by the river due to avulsion and incision-driven course changes. We have recorded the nature of the outwash gravels, now effectively terrace features, from exposed sections in working quarries, one of which we discuss here. The palaeochannels have accumulated sediment fills and we have examined several which lie within the range of 100 and 16 m above present sea level. The results of lithostratigraphic, palynological, and radiocarbon analyses at two main and three subsidiary sites indicate that palaeochannel ages range from almost 14,000 to approximately 4000 calibrated years ago in a clear altitudinal sequence. The oldest are probably caused by rapid incision due to deglaciation-driven isostatic uplift. The similarity in date of the three downstream sites suggests that a late Holocene combination of climatic deterioration and increased human activity in the catchment caused instability and entrenchment. Pollen data from the channel fills provide relative dating, and agree well with pollen records from other regional Lateglacial and Holocene sites. Non-pollen palynomorph (NPP) analysis at one of the sites allows reconstruction of the hydrological history of channel infill. This research shows that the application of an integrated suite of research techniques can yield a highly detailed understanding of fluvial evolution and landscape history.

Keywords: North Yorkshire; River Ure; geomorphological mapping; palynology; fluvial evolution; fluvioglacial sediment

1. Introduction

The sedimentary and palaeoenvironmental records from deglaciated landscapes form an important archive that provides information regarding the timing and rate of deglaciation, and allows reconstruction of fluvial history, including the re-establishment of drainage systems and their influence on the development of the wider landscape [1,2]. In this paper, we present the results of an integrated survey of a short, mid-altitude reach of the Ure river valley in North Yorkshire, UK, which, by combining the mapping of deglacial deposits and geomorphological features with palaeoenvironmental analyses of Lateglacial and post-glacial sediments, provides

a detailed record of the evolution of fluvial systems and associated landscapes during and after the retreat of ice sheets from the uplands of the Central Pennine hills in northern England. Several rivers drain the eastern slopes of the Pennines in North Yorkshire and are tributaries to the river Ouse, which occupies the lowland Vale of York and eventually reaches the sea via the Humber Estuary on England's east coast. The River Ure, running through the west-east-trending valley of Wensleydale, is one of the main headwaters of the Ouse, which it forms after confluence with the more northerly river Swale (Figure 1b). Along with most of northern England, including the lowland Vale of York, the Pennines were ice covered during the Last (Devensian) Glacial Maximum (LGM) [3–5], with Wensleydale having its own valley ice stream [6]. Deglaciation resulted in the deposition, by large volumes of meltwater, of substantial spreads of glaciofluvial sand and gravel outwash on the eastern flanks of the upland, as well as the incision of meltwater channels of various sizes into this thick surface veneer of clastic sediment, over which the rivers established their post-glacial courses on their way to the Vale of York. As with the other northerly rivers on the flanks of the eastern Pennines, the proto-Ure was deflected southward by the ice remaining in the Vale of York [7]. These rivers were initially gravel-bed, high-energy braided river systems with active floodplains and frequently avulsing channels [8]. They then cut deep valleys in the glaciofluvial outwash sediments, creating terraces and redistributing large amounts of sand and gravel downstream. In their middle 'piedmont' reaches, locally termed 'washlands', where lower gradients and wider valleys reduced flow rates, there was aggradation, with rivers reoccupying established channels and depositing the sands and gravels as stacked valley fills [9–13]. These clastic valley-fill sequences can be extremely thick and have provided a valuable resource of aggregates, leading to the excavation of numerous sand and gravel quarries in the Ure valley.

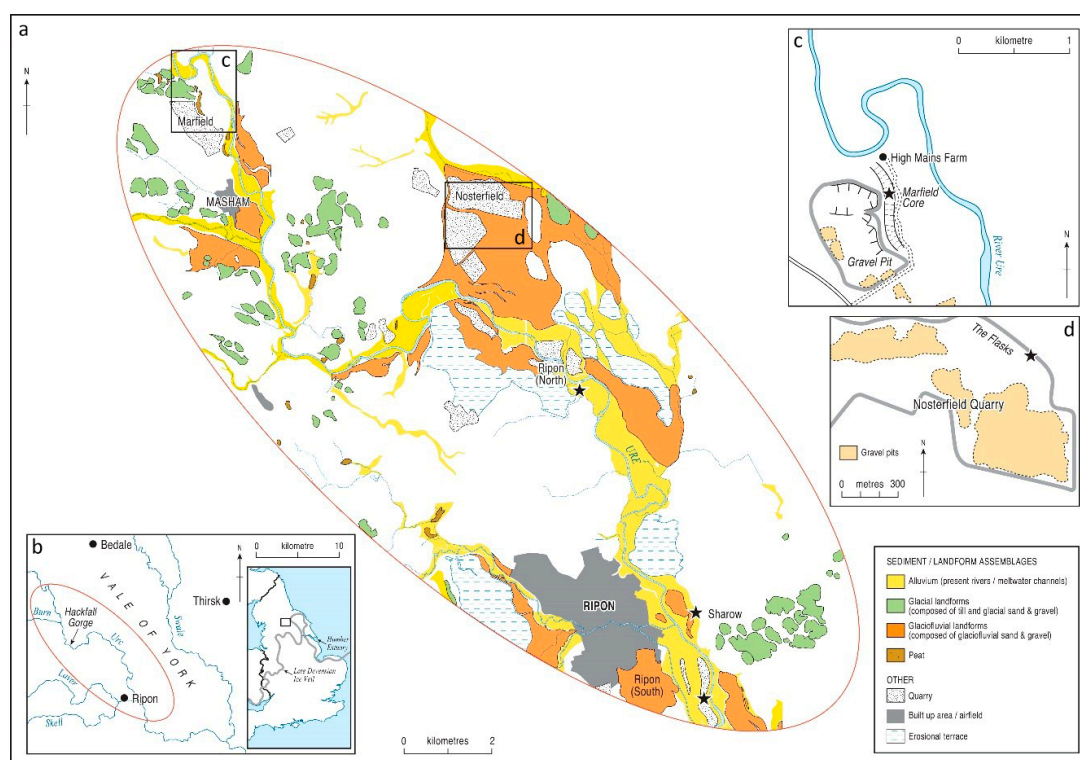


Figure 1. Results of our field mapping of the distribution of river alluvium and other surficial sediments in the Ure valley (a) and location of the Ure valley between Marfield and Ripon in North Yorkshire (b). The insets show details of the two main study sites at Marfield (c) and Nosterfield, The Flasks 69 (d). Other sites at Ripon North, Sharow Mires and Ripon South are also shown, and all core locations are indicated by black stars. A schematic cross-section of the valley between Marfield and the Ure south of Ripon, showing major sites and features, is presented below.

This paper reviews the findings of research into the fluvial and environmental history of the washland reaches of the River Ure valley from north of Masham to south of Ripon (Figure 1), work undertaken in advance of quarrying in areas scheduled for aggregate extraction, at sites which quarrying would destroy, and at sites where an exceptionally important research archive was likely to be preserved [14,15]. The aim of this project was therefore to preserve data from threatened sedimentary archives, but also to improve overall understanding of the Lateglacial and Holocene fluvial and landscape evolution of the study area. The project data are deposited with the Archaeology Data Service UK [16] and are available for public access. In this paper, we present Lateglacial and early Holocene data from Ure valley sites at Marfield and Nosterfield (the Flasks), with brief reference to later Holocene sequences near Ripon, downstream of these two major study sites (Figure 1), which provide insights into the dates of channel abandonment [17,18] at different points along the valley.

2. Materials and Methods

2.1. Study Area: Regional Context and Research Site Setting

2.1.1. The Central Pennines (Yorkshire Dales)

The area of study lies in the Yorkshire Dales, which form the northern part of the Central Pennine hills in northern England. The Central Pennines are composed firstly of sedimentary rocks of Lower Carboniferous limestone, overlain by the Yoredale Series (Wensleydale Group) of limestones, shales and sandstones, and then by the sandstones of the Millstone Grit, bounded to the east by a ridge of Permian Magnesian limestone [19,20], and together form the Askrigg Block. The later, more resistant, sedimentary units form horizontally-bedded strata so that the summits of the upland are mainly flat plateaux areas which support moorland vegetation comprising heath and rough grassland. Only a few hills, with a maximum elevation a little over 700 m, rise above the upland plateaux. The Central Pennines are dissected by several large river valleys, the Dales, which drain the upland to east and west. These are heavily incised in their upper reaches, including the study valley of the River Ure, although form broader, low-gradient valleys at lower altitudes. The relative roles of base-level change and/or uplift are topics of debate regarding this heavy incision and, although this area has been undergoing slow, long-term uplift since pre-Quaternary times [21], it is likely to have been a response to crustal rebound after the removal of last Glacial ice [1]. The glaciation of the Central Pennines has long been recognized [22–24], and most or all of the visible evidence can now be attributed to glaciation during the LGM (5). Indeed, there is widespread cover of glacial sediments and the solid geology is rarely exposed, excepting in eroded limestone glaciokarst pavements, eroded spurs such as Kilnsey Crag in Wharfedale [25], rock-cut gorges such as Hackfall Gorge on the Ure [18] or in ‘scars’ on fault lines at the edges of the Askrigg Block, as at its southern border at Giggleswick Scar [26]. Although the Central Pennines probably nurtured local ice accumulation in a few high locations [25,27], it is likely that the upland was over-ridden by ice from major glacial centres to the north and west [5,27]. The rivers of the Yorkshire Dales therefore flow through valleys that have been modified by glaciation [28]. The geomorphology of the Yorkshire Dales is mostly paraglacial [29], and within the valleys are moraines of glacial debris that mark the extent of ice advance or stages in its retreat, and drumlins are common features at all altitudes in the valleys [30–32], often streamlined due to ice-stream movement [33], revealing the direction of ice flow. Many other landforms in the Central Pennines indicate the consequences of ice removal, with intense fluvial activity during deglaciation. Rapid river incision into glaciofluvial sands and gravels deposited during deglaciation caused abandoned floodplain surfaces to be preserved as river terraces, often as a series as is well preserved in Upper Wharfedale [34], while meltwater channels, now dry, formed either subglacially or ice marginally as ice retreated into the upland, and are abundant throughout the Yorkshire Dales, but particularly near Ripon. Meltwater also formed esker ridges at ice margins and glacial lakes impounded by morainic material, as at the entrances to the eastern Dales, particularly Wensleydale and Swaledale [18].

While the legacy of deglaciation in the Central Pennines is clear to see in terms of landforms and sediments, the timing of its start and of its various stages is much more difficult to deduce, as erosional landforms and clastic deglacial deposits are difficult to date directly, although promising attempts have been made in Wharfedale [35] with U-series dating. Cosmogenic dates from Stainmore, at the northern edge of the Central Pennines, indicate decoupling of the North Sea Lobe and Stainmore ice prior to ~20 ka, followed by ice recession through the Stainmore Gap by 19.8 ± 0.7 to 18.0 ± 0.5 ka [36]. No organic deposits in the Yorkshire Dales extend back in time to the LGM–Lateglacial transition and the few Lateglacial sites, as at Lunds near the source of the Ure [37] and at Malham Tarn Moss [38] are not radiocarbon dated. The driver for deglaciation in the study area, as elsewhere, was climate and several climate events can be recognized, operating at centennial and millennial scales, superimposed on the tripartite Lateglacial Stadial/Lateglacial Interstadial/Loch Lomond Stadial gross subdivision of the Lateglacial [39,40]. Broadly, the climate changes after the LGM termination at approximately 15 ka ^{14}C BP can be summed up (in radiocarbon years) as five centuries of slow warming, followed by five centuries of significant cooling, then a millennium of gradual warming until 13 ka BP. Abrupt warming then occurred (start of the Interstadial) until 12.4 ka BP followed by a cooling phase until 12 ka BP. Warming then occurred until 11.4 ka BP, followed by a brief cooling phase until 11.2 ka BP, then climate warming from 11.2 to 10.9 ka BP (end of the Interstadial). This was followed by the Loch Lomond Stadial, with a severe cold phase until 10.5 ka BP, and then cold, arid conditions until 10.0 ka BP, after which abrupt warming marked the start of the Holocene. In the study area of the Central Pennines, each of these climate fluctuations would lead to glacier re-advance or retreat during the general process of deglaciation, would govern the fluvial history of the area, and would determine the pattern of erosion and deposition in the Central Pennine valleys. The fluvial geology of a section of the River Ure has been subject to detailed investigation in this regional context.

2.1.2. Geology of the Ure Washlands

The ‘piedmont’ (washland) reaches of the River Ure run across two of the bedrock units mentioned above [18,27,41]. Upstream, to the north-west, lies the sandstones and shales of the Wensleydale Group of the Pennine Carboniferous series, upon which lies the study site at Marfield, just below the point where the course of the Ure was deflected southward by ice blocking its original valley, with the Carboniferous extending downstream to the end of the Hackfall Gorge (Figure 1b). Further south-east are Permian rocks, mainly limestones, which overlie the Carboniferous, the river flowing over these to the end of the study area just south of Ripon (Figure 1). The Hackfall Gorge is the most impressive landscape feature of this section of the Ure valley, and was formed where the deflected early Ure encountered the Permian (Magnesian) escarpment and cut through it, the river incising over 40 m in only a 3 km stretch of valley. Elsewhere in the Ure valley, the bedrock is obscured by a thick cover of superficial sediments, glacial tills (diamicton), sands and gravels, deposited during the last glacial period. These are overlain by the glaciofluvial meltwater sands and gravels laid down during deglaciation, as described above. These form terrace features, with their distribution within the study reach of the Ure valley being shown on Figure 1b. Below the exit of the Hackfall Gorge at Nosterfield is an extensive fan of fluvially-deposited sand and gravel (Figure 1d), formed at the end of the glacial, and a legacy of the severe downcutting that formed the gorge. The second major site in this paper, the Flasks 69, lies upon this fan. The uppermost deposit in the Ure valley is riverine alluvium, present in the current river valley and in abandoned river channels. In places, Lateglacial and Holocene peat deposits rest within and upon the earlier formations. The bedrock and its influence upon deglaciation, has been instrumental in determining the nature of deglaciation, and thereby fluvial history.

2.2. Research Techniques

Geomorphological mapping in the middle Ure valley involved the field survey of 6 to 8 km² per day, recording the spatial distribution of landforms and superficial deposits and interpreting these in terms of geomorphological processes and their role in landscape evolution [42]. Positive landscape features such as ridges and mounds and negative features including channels and depressions were identified by mapping breaks of slope and plotting these on a 1:25,000 Ordnance Survey topographic map, along with flatter areas that represent fluvial terraces or ancient lake beds. The map provides the basis for a detailed explanation of the geomorphological evolution of the Swale-Ure Washlands [18]. The mapped section relevant to the River Ure between Marfield and Ripon is presented as part of Figure 1, with the distribution of alluvium, glacial and glaciofluvial landforms, peat and the location of quarries shown.

Sediment sequences for lithological and palaeoenvironmental analyses presented in this paper were sampled using a Russian-style corer. Several techniques were used to investigate the sediment profiles in order to reconstruct their development and local environmental conditions. Pollen analysis was employed to allow the reconstruction of vegetation history [43], and to enable a relative age to be assigned to Lateglacial and early Holocene deposits, based upon comparison with other nearby, radiocarbon dated, pollen profiles, e.g., [18,44]. Samples were prepared for pollen analysis using standard techniques [45], using KOH and acetolysis, with HCL and HF in samples with a mineral content. These procedures do not affect the preservation of most non-pollen microfossils such as algal and fungal spores [46]. Pollen residues were stained with safranin, then mounted on microscope slides using silicone fluid. Counts of at least 300 land-pollen grains were made using a standard light microscope at $\times 400$, with pollen nomenclature following Moore et al. [45]. Pollen frequencies were calculated as percentages of a total land-pollen sum, which comprises trees, shrubs and herbs but excludes aquatics and all spores. The pollen diagrams show selected major taxa and taxa groups but exclude those with very low and sporadic counts. Several taxa are combined into groupings based upon their similar life-form and ecology. Of these groupings, 'tundra/ruderal herbs' contains *Artemisia*, *Helianthemum*, *Thalictrum*, *Chenopodiaceae*, *Rumex*, *Saxifraga stellaris*-type, *Sedum*, *Silene*-type, *Taraxacum*-type, *Plantago maritima* and *P. lanceolata*. 'Marsh/wetland herbs' contains *Filipendula*, *Potentilla*-type, *Cirsium*-type, *Mentha*-type, *Ranunculus*-type, *Stellaria*-type and *Umbelliferae*. 'Aquatics' contains the rare records for *Myriophyllum alterniflorum*, *M. spicatum*, *Nymphaea* and *Potamogeton*. *Typha angustifolia* and *T. latifolia* curves are shown separately.

Frequencies of micro-charcoal (particles < 180 μm and thus passing through the sieve used in the preparation schedule) were calculated as percentages of the pollen sum, as described in previous papers [47], as were those of non-pollen palynomorphs (NPPs). These were counted on the pollen slides, identifications made using the catalogue developed at the Hugo de Vries Laboratory, University of Amsterdam [48] and illustrations and descriptions published in various papers [49–53]. One hundred NPPs were counted per level where possible, although at several levels concentration was too low, although counts always exceeded fifty. Established NPP names are used where known, with the catalogue (HdV) code number shown upon first citation. Where NPP names are unknown, the catalogue code number is used throughout. Microfossil diagrams were produced using the TILIA program [54]. Radiocarbon dating [55] was carried out by the Oxford Radiocarbon Accelerator Unit at the University of Oxford using Accelerator Mass Spectrometry (AMS), at the Centre for Isotope Research, Groningen University, Netherlands, and at the Scottish Universities Research and Reactor Centre, East Kilbride. All dates were by Accelerator Mass Spectrometry (AMS). Material for dating was restricted to terrestrial plant macrofossils such as seeds, fruits and bark fragments. Plant roots, aquatic macrofossils and bulk sediment were avoided, with levels chosen for dating decided by the availability of suitable macrofossils. Details of radiocarbon results from the sites mentioned in this paper are shown in Table 1, calibrations being derived using Oxcal 4.2 and IntCal13 [56]. Lithos-

stratigraphy was recorded using the notation devised by Troels-Smith [57], as described by Long et al. [58], and is used in Tables 2 and 3 as well as descriptions in English.

Table 1. Sample details and radiocarbon data from Nosterfield, the Flasks 69 and from other Ure valley fluvial channel sites [18]. Calibrated age ranges (2 σ) and means are derived using Oxcal 4.2 and IntCal13 [56].

Site Lab Code	Depth (cm)	Lab Code	¹⁴ C Date (yr BP)	Mean Age (cal. BP)	Age Range (cal. BP)
Flasks 69	49–50	OxA-12960	8725 \pm 45	9552–9888	9720 \pm 168
Flasks 69	83–85	OxA-12932	9990 \pm 45	11,264–11,701	11,482 \pm 218
Flasks 69	153–154	OxA-12972	10,510 \pm 55	12,154–12,608	12,381 \pm 227
Flasks 69	163–164	OxA-12997	10,920 \pm 45	12,641–12,935	12,788 \pm 147
Sharow Mires	954	SUERC-8881	3905 \pm 35	4236–4426	4331 \pm 95
Ripon North	69–70	GrA-25377	2325 \pm 50	2157–2488	2322 \pm 165
Ripon North	c.82	Gu-5998	3900 \pm 50	4155–4499	4327 \pm 172
Ripon South	32	OxA-12636	4011 \pm 40	4411–4781	4596 \pm 185

Table 2. Lithostratigraphy at Marfield High Mains Channel. Altitude + 100 m a.s.l.

Depth (cm)	Description
0–16	Amorphous, slightly silty organic material Sh4, Ag+, nig.4, strf.0, elas.0, sicc.2
16–39	Orange brown shell marl with organic inclusions and Turritellids (some whole) Lc4, Sh+, test. (moll)+, part. test. (moll)+, nig.1, strf.0, elas.0, sicc.2, lim.sup.0
39–66	Brown silty humified peat with some clay Sh3, Ag1, As+, nig.3, strf.0, elas.0, sicc.2, lim.sup.0
66–79	Black well-humified peat Sh4, nig.4, strf.0, elas.0, sicc.2, lim.sup.0
79–166	Buff shell-marl with silt and organic material Lc3, Ag1, part. test. (moll)+, Sh+, nig.1, strf.0, elas.0, sicc.2, lim.sup.0
166–175	Green-grey silty shell-marl with organic inclusions Lc4, Ag+, part. test. (moll)+, Sh+, nig.1, strf.0, elas.0, sicc.2, lim.sup.0
175–190	Dark grey clayey silt with shells and some gravel Ag4, As+, part. test. (moll)+, Gg(min.)+, nig.2, strf.0, elas.0, sicc.2, lim.sup.0
190–210	Grey clayey silt with shells and gravel Ag3, As1, part. test. (moll)+, Gg(min.)+, nig.2, strf.0, elas.0, sicc.2, lim.sup.0
210–225	Gravel Gg(min)4, nig.2, strf.0, elas.0, sicc.2, lim.sup.0
225–246	Clayey silt with small gravel Ag2, As1, Gg(min)1, nig.2+, strf.0, elas.0, sicc.2, lim.sup.0
246–276	Buff sandy shell marl with occasional small gravel Lc2, Ga2, part. test. (moll)+, Gg(min)+, nig.1, strf.0, elas.0, sicc.2, lim.sup.0
276–308	Dark grey clayey silt with shells and organic inclusions Ag3, As1, part. test. (moll)+, Sh+, nig.2+, strf.0, elas.0, sicc.2, lim.sup.0
308–329	Dark grey clayey silt Ag3, As1, nig.3, strf.0, elas.0, sicc.2, lim.sup.0

Table 3. Lithostratigraphy at Nosterfield, the Flasks 69. Altitude 39.26 m a.s.l.

Depth (cm)	Description
0–45	Topsoil
45–75	Crumbly humified amorphous peat. Sh4, nig.4, strf.0, elas.0, sicc.3, lim.sup.0
75–86	Herbaceous detritus peat. Charcoal present from 80 to 85 cm. Dh4, anth.+++ , nig.3, strf.0, elas.0, sicc.2, lim.sup.0
86–96	Brown organic shelly silt with limus. Ag3, Ld ³ 1, Sh+, part.test.(moll.)+, nig.2+, strf.0, elas.0, sicc.2, lim.sup.0
96–110	Grey-yellow silt clay. As2, Ag2, nig.2, strf.0, elas.0, sicc.2, lim.sup.2
110–153	Grey clay silt with limus. Ag2, As1, Ld ³ 1, nig.2+, strf.0, elas.0, sicc.2, lim.sup.0
153–164	Brown limus Ld ³ 4, nig.2+, strf.0, elas.1, sicc.2, lim.sup.0
164–166	Grey silt clay. As2, Ag2, nig.2, strf.0, elas.0, sicc.2, lim.sup.1
166–200	Grey-yellow silty shell marl. Lc3, Ag1, part.test.(moll.)+, nig.2, strf.0, elas.0, sicc.2, lim.sup.0
200–235	Grey-yellow clay silt with sand. Ag2, As2, Ga++, nig.2, strf.0, elas.0, sicc.2, lim.sup.1

2.3. Research Sites

Two separate sites were investigated at Marfield: Marfield Quarry (Figures 1 and 2), where gravel outwash sequences were exposed in association with glacial diamicton [59], and the High Mains Channel (Figures 1 and 3, 54°14'26" N, 1°40'4" W), a palaeochannel located to the east of the quarry. The channel has been truncated by aggregate extraction, but several hundred metres remain intact. Now more than 10 m above the present river, it would have been an early course of the River Ure, which was abandoned after the river began to incise rapidly through the glaciofluvial deposits that are exposed in the quarry. Together, the two sites at Marfield provide an excellent example of deglacial fluvial history and processes, with ice-marginal outwash sedimentation and the response of a drainage system that has re-established and adjusted its course across the fluvial outwash deposits.

A site was investigated, on the Nosterfield outwash fan (Figure 1) at The Flasks, one of many small drainage channels incised into its surface within which sediment sequences have accumulated since Lateglacial times, as shown by pollen analysis and radiocarbon dating [18,60,61]. These sequences comprise both clastic and organic sediments and represent a long-term record of climatic change since deglaciation. Several of these sediment-filled channels were located during a survey by archaeologists of Mike Griffiths Associates Ltd., and we selected one of them, at core 69 (Figure 1, 54°13'20" N, 1°33'55" W), for integrated palaeoenvironmental analyses.



Figure 2. Exposures of fluvio-glacial outwash gravels exposed in the southeastern part of Marfield Quarry (photo 2004 by David Bridgland), with David Roberts shown as scale. The gravel sequence is capped by a thin surface till, indicating a brief period of local Wensleydale ice re-advance.

Although microfossil analyses are not presented in this paper, three other sites near to Ripon have been selected to assist the discussion as they have data which are relevant to fluvial history in the later Holocene in that part of the Ure valley, complementing the Lateglacial and early Holocene records at Marfield and The Flasks 69. These sites (Figure 1) are at Sharow Mires ($54^{\circ}8'18''$ N, $1^{\circ}30'14.6''$ W), Ripon North ($54^{\circ}11'6.7''$ N, $1^{\circ}32'14''$ W) and Ripon South ($54^{\circ}7'0''$ N, $1^{\circ}29'31.5''$ W). Their dating results are shown in this paper (Table 1) and their full analyses are available elsewhere [18].

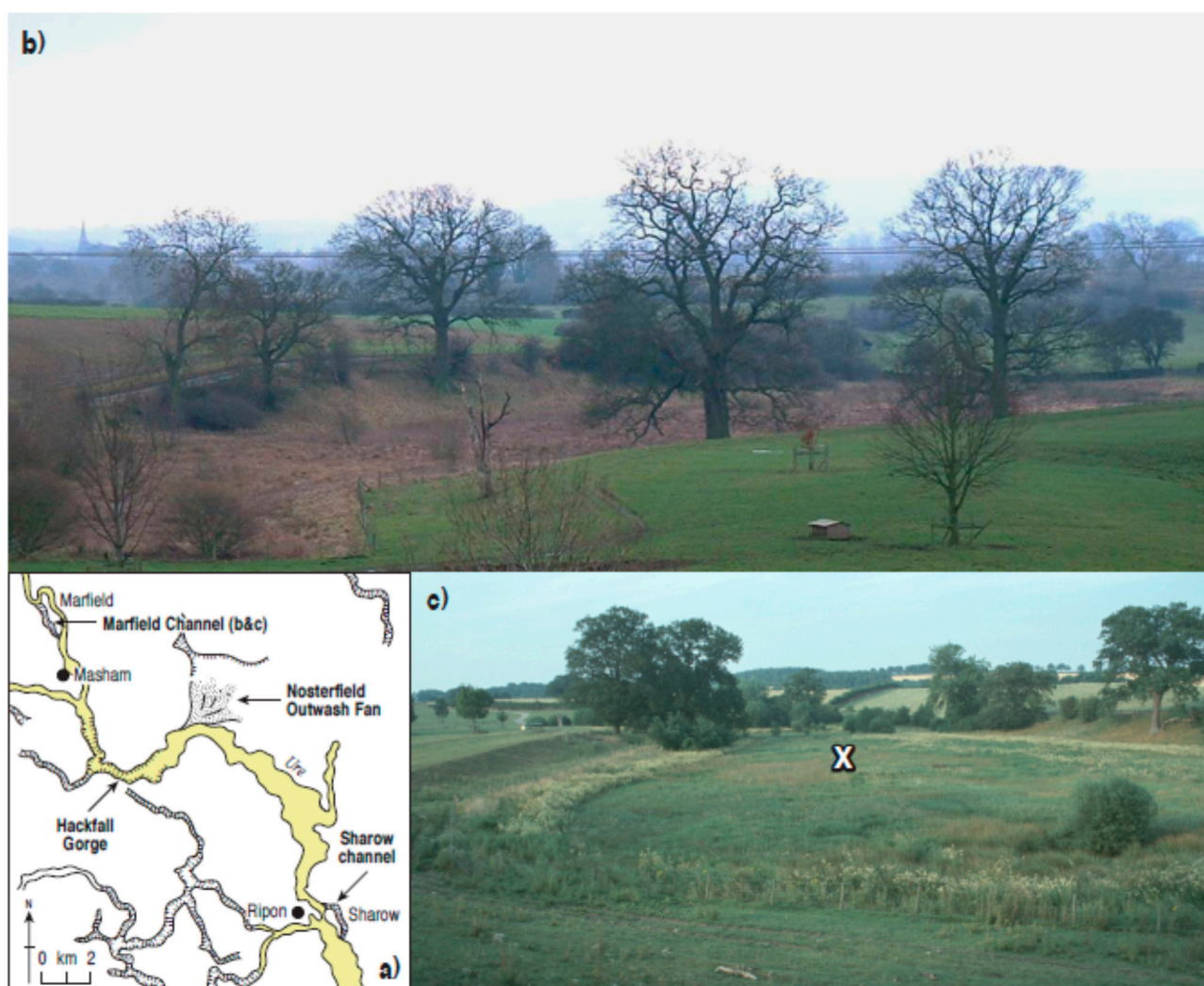


Figure 3. (a) Location of geomorphological channel features mentioned in the text. Yellow shading indicates alluvial sediments in the current Ure valley. (b) The High Mains abandoned channel of the Ure at Marfield. (c) View towards the location of the coring site at Marfield, which is marked with an X, looking north. Photographs by Wishart Mitchell. For detailed location of the channel relative to the River Ure and the Marfield Quarry, see Figure 1.

3. Results

3.1. Marfield Quarry

Moraine ridges at Marfield Quarry are evidence of an oscillating ice margin, probably a lobe associated with the Wensleydale valley glacier that experienced periodic withdrawal and readvance, shown by the thin subglacial till that caps thick sand and gravel outwash sequences exposed in the southeastern part of the quarry (Figure 2). These gravels are excellent examples of ice-marginal deposits [62] and illustrate the power of high-energy meltwater streams in redistributing fine- and coarse-grained clastic material eroded from the ice front. They fine upwards, showing the reducing energy of the fluvial outwash as the ice receded up the valley away from Marfield, before being briefly over-ridden again before final deglaciation. The Marfield Quarry outwash sediments are important, as they allow the fluvial history of this upper part of the Ure Washlands to be reconstructed since deglaciation, and linked to the subsequent fluvial history of sites downstream. They lie 30 m above the present Ure valley floor, and can be regarded as the highest in the sequence of gravel terraces within the river valley which record progressive incision of the river into the outwash deposits. Evidence for this incision at quite an early stage is provided by the High Mains Channel (Figure 3a), which must be an early abandoned channel of the

Ure. After the river abandoned its course through this channel, it became filled with later sediments which rest upon the outwash gravels.

3.2. Marfield High Mains Channel

Cores were obtained of the sedimentary infill of this channel [63], which lies between the quarry and the River Ure at an altitude of approximately 100 m above sea level (Figure 3c). The analysed core was almost 330 cm in depth before encountering a hard surface, probably gravel, which could not be penetrated. The core lithology is shown in Table 2. Most of the sediment comprises shell-rich marls and clayey silts of a kind probably deposited in the open water of a fluvial channel or a pond, which was later confirmed by microfossil analysis. The upper part of the sequence comprised well-humified peat, slightly clayey at intervals, which contained a layer of shell marl. This lithology suggests that the channel was occupied by a water body for most of its history after the river left it and it became a cut-off depression in the landscape.

3.2.1. Marfield Channel Palynology

Subsampling for pollen analysis took place at ten-centimetre intervals. Not all levels preserved pollen, with five samples within a stiff lower clayey silt and gravel unit and two samples within the upper peat layer barren of microfossils. Pollen preservation in the counted samples was variable but often poor. Seven pollen assemblage zones (PAZ) have been recognized, with the barren layers excluded from the diagram zonation. A selected-curve diagram is provided in this paper (Figure 4); the full pollen diagram is available elsewhere [60]. The diagram is divided into the following PAZs which include pollen counts at the depths shown.

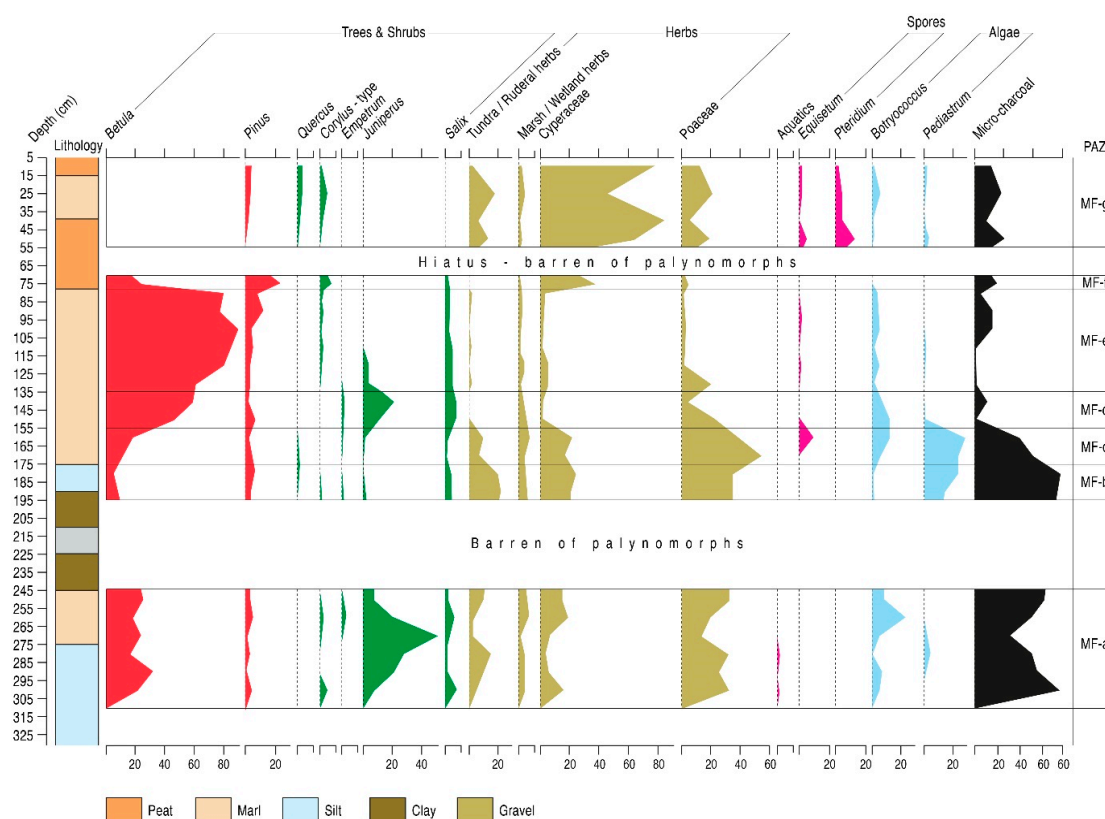


Figure 4. Summary pollen diagram from Marfield. Frequencies are calculated as percentages of total land pollen. For lithology, see Table 2.

(1). Zone MF-a: 300, 290, 280, 270, 260 and 250 cm

The zone is characterized by moderate *Betula* frequencies at approximately 30% of total land pollen (tlp), with shrub pollen represented by *Salix* and, particularly, *Juniperus*, which is present throughout and reaches a peak of almost 50% in mid-zone. A small peak of *Empetrum* occurs late in the zone. Poaceae is the most abundant of the herbaceous taxa, consistently reaching approximately 30%, with lesser frequencies of Cyperaceae, tundra/ruderal herbs and wetland herbs. *Artemisia*, *Helianthemum* and *Thalictrum* are the most prominent of the open ground weeds. The algae *Pediastrum* (HdV-760) and *Botryococcus* (HdV-766) are present, particularly the latter. Micro-charcoal counts are high throughout the zone.

(2). Zone MF-b: 190 and 180 cm

Betula frequencies are very low, *Juniperus* is hardly recorded but *Salix* levels are similar to the previous zone, as are those for Poaceae and Cyperaceae, although the latter are slightly increased. Tundra/ruderal weeds are significantly increased, comprising mainly *Artemisia*, *Saxifraga stellaris*-type and *Thalictrum*. Marsh/wetland herb percentages change little from the earlier zone. Peaks of *Pediastrum* occur and micro-charcoal frequencies are high.

(3). Zone MF-c: 170 and 160 cm

This zone is characterized by high Poaceae frequencies, reaching well over 50% of tlp. Cyperaceae percentages are maintained from the previous zone at over 20%. Tundra/ruderal herb frequencies have fallen considerably, and *Artemisia* has been replaced by *Rumex* as the main constituent of the group. *Betula* percentages rise through the zone, although remain moderate. Marsh/wetland herbs change little from their values in earlier zones. *Pediastrum* values are particularly high at almost 30%, whereas wetland types *Botryococcus* and *Equisetum* show lesser peaks. Micro-charcoal frequencies are still significant but decline through the zone.

(4). Zone MF-d: 150 and 140 cm

Tree and shrub pollen dominate the assemblage, with *Betula* rising through the zone to 60%, *Juniperus* peaking at 20% and *Salix* consistent at approximately 10%. Poaceae decline sharply, whereas Cyperaceae and tundra/ruderal herb percentages fall until they are hardly represented. Marsh/wetland herbs remain at the values recorded previously. *Botryococcus* is still recorded at a little over 10%, but *Pediastrum* and *Equisetum* are absent. Micro-charcoal falls to low frequencies.

(5). Zone MF-e: 130, 120, 110, 100, 90 and 80 cm

This zone is dominated almost entirely by *Betula*, which rises to over 80% of tlp. *Juniperus* declines sharply and by mid-zone ceases to be recorded. All other taxa and groupings are very poorly represented, although *Salix* counts are similar to those earlier in the profile. *Botryococcus* remains present at low values but *Pediastrum* is virtually absent. Micro-charcoal frequencies are low and intermittent.

(6). Zone MF-f: 75 cm

This single-level zone records a major fall in *Betula* percentages, while *Pinus* rises to over 20%, *Corylus*-type shows a small peak at almost 10%, and *Salix* values are maintained. Cyperaceae frequencies rise to 50% of tlp, and all other curves are in very low percentages, except micro-charcoal which is in moderate frequencies.

(7). Zone MF-g: 50, 40, 25 and 10 cm

Cyperaceae dominate the assemblage, reaching over 80% of total land pollen. Poaceae and tundra/ruderal herb percentages are moderate at approximately 20%, with *Taraxacum*-type and *Plantago lanceolata* prominent in the ruderal assemblage. *Pteridium* occurs in significant percentages of over 10%. All other pollen taxa are low, including trees and shrubs, with *Corylus*-type and *Quercus* present in low frequencies. *Equisetum* returns

to the assemblage, and *Botryococcus* and *Pediastrum* still occur, but in low frequencies. Micro-charcoal percentages remain moderate.

3.2.2. Dating, Hydrology and Environment of Deposition

Unfortunately no suitable terrestrial macrofossils could be recovered from the Marfield core for radiocarbon dating and so the profile has no direct chronological control. Relative dating is possible, however, by comparison of the pollen assemblages with nearby Lateglacial profiles that have been radiocarbon dated, in particular pollen diagrams [18,60] from Mill House at Snape Mires and from the Flasks 69 (see below), both of which have a good series of four dates. The rise of *Juniperus* to peak values in PAZ MF-a correlates well with a similar period of high *Juniperus* values at the nearby Mill House 1 profile [60], and suggests that the base of the Marfield diagram can be dated broadly between 12,000 and 11,500 ^{14}C years ago, approximately 13,500 calibrated yr BP, during the mid-Lateglacial Interstadial. The clay layer and high *Artemisia* values in PAZ MF-b point to a Loch Lomond Stadial age, after c. 11,000 ^{14}C BP, analogous to that level at both Mill House 1 and the Flasks 69. The succession from MF-c onwards is clearly that of the early Holocene, with initial high Poaceae and *Pediastrum*, and the beginnings of a rise in *Corylus*-type pollen in PAZ MF-f suggest a date of approximately 9000 ^{14}C BP for that point in the diagram.

The dating of PAZ MF-g, after an apparent hiatus in the profile, is problematic but the lack of woody taxa and dominance of open-ground herbs with sedges and *Pteridium* points to a date in the late Holocene.

The clay, marl and limnic sediments at Marfield indicate open water deposition within the channel after its abandonment by the river approximately 12,000 ^{14}C BP, in the centuries after c. 14,000 cal. BP, which is supported by the presence of *Botryococcus* algae throughout the profile, suggesting cool, mesotrophic open water [51,64], accompanied by lower values of *Pediastrum*. The near absence of aquatic pollen throughout the profile might represent the position of the core in the centre of a wide channel, away from the habitat of any aquatic plants at the channel fringes. The presence of shelly marl sediments with *Botryococcus* in mid-PAZ MF-g indicates continued aquatic deposition, perhaps during a flooding period if the amorphous peats of that upper part of the profile indicate more terrestrial depositional environments within a soligenous mire, in what must equate with the later Holocene.

3.2.3. Vegetation History

The relative dating of the Marfield profile to a period between the middle of the Lateglacial Interstadial and the start of the early Holocene *Corylus* rise, so c.12,000 to c.9000 ^{14}C BP, means that the vegetation changes are typical of that climatically transitional period. PAZ MF-a saw the expansion of *Juniperus* and *Betula* woodland, but the high values for Poaceae, Cyperaceae and terrestrial herbs show that these woods remained very open. PAZs MF-b to f record a typical early Holocene succession from tall herb communities through *Empetrum* and *Juniperus* scrub to closed canopy *Betula* woodland. The vegetation of PAZ MF-g, of unknown late Holocene age, was clearly very open. Even if the high Cyperaceae percentages reflect local sedge dominance of the mire surface, the high *Pteridium* and ruderal herb values and the lack of tree and shrub pollen indicate a deforested landscape, perhaps of quite recent age.

3.3. Nosterfield, the Flasks 69

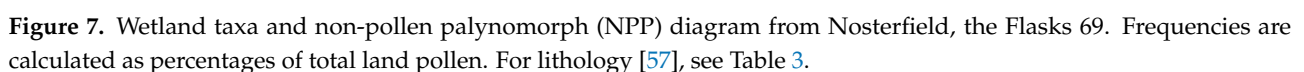
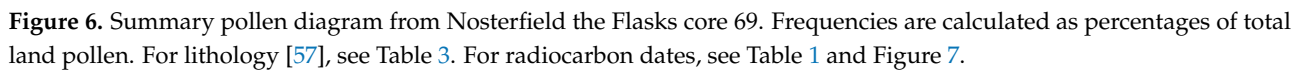
A core was recovered from this site at Nosterfield Quarry (Figure 5a) which was 235 cm in depth. Here we report on the results of lithostratigraphic and palynological investigations. The core lithology (Table 3) records shelly marl and limnic units separated from an upper detrital and humified peat sequence by a silty clay layer, all resting upon stiff clays and gravel.



Figure 5. (a) Aerial photograph (2003) of Nosterfield Quarry, looking south, by Wishart Mitchell. The location of the Flasks 69 profile is marked with an X. (b) Aerial photograph of palaeochannels visible in the Nosterfield outwash fan (Dr. Peter Addyman). (c) Example of the sediment fill of one of the Nosterfield palaeochannels, showing a tripartite sequence (Mike Griffiths Associates). For location of Nosterfield Quarry, see Figure 1.

3.3.1. The Flasks 69 Palynology

Subsampling for pollen analysis took place at five-centimetre intervals through the core, and only a few levels did not preserve countable pollen, although preservation was generally only moderate, with a degree of grain corrosion apparent. Sampling at closer intervals occurred in the upper part of the profile, in order to establish pollen zone boundaries more closely and so aid selection of levels for radiocarbon dating. The detailed pollen diagram has been published previously [18,60], so a selected curve diagram is provided here (Figure 6). Eight pollen assemblage zones (PAZs) have been recognized and these have been applied to the NPP diagram from the Flasks 69 (Figure 7), which also shows the main wetland pollen and spore types from Figure 6. The PAZs include pollen counts at the depths shown.



In this single-level zone, trees and shrubs account for approximately 40% of tlp, almost entirely comprising *Betula*, *Juniperus* and *Salix*, with *Betula* most abundant at 20%. Overall Cyperaceae is the most prominent pollen type, at 30%, with Poaceae also important, at

approximately half that frequency. Marsh/wetland herbs representation is very low, but the tundra/ruderal herbs group reaches 10%. Micro-charcoal frequencies are moderate.

Few NPPs are recorded, all algal spores, and in low frequencies. Type HdV-128 occurs at almost 20% of tlp, while *Pediastrum* and *Closterium* (HdV-60) are present in lower frequencies.

(2). Zone F69-b: 170 and 175 cm

Betula percentages increase slightly and both *Juniperus* and *Salix* are reduced. *Empetrum* occurs for the first time. Cyperaceae and Poaceae values are little changed, except that the former increases slightly at the expense of the latter. Tundra/ruderal herb frequencies increase significantly, caused mainly by a rise in *Artemisia*, and there is a greater diversity of taxa, with *Helianthemum*, *Plantago maritima* and *Rumex* joining the assemblage. The marsh/wetland herbs curve remains very low. Very few other taxa are recorded, although there are isolated grains of the aquatic *Typha angustifolia*. Micro-charcoal values remain moderate at a little over 20%.

Amongst the NPPs, HdV-128, *Pediastrum* and *Closterium* are still the most abundant taxa, but also present in low frequencies are *Cosmarium* (HdV-332) and Copepoda (HdV-28).

(3). Zone F69-c: 164, 160, 155, 150, 145, 140, 135, 130, 120 and 110 cm

In this zone, *Betula* frequencies fluctuate but are consistently approximately 20% of tlp. *Salix* percentages remain steady at approximately 10% but *Juniperus* declines to very low values. *Pinus* becomes better represented in the latter half of the zone. The assemblage is dominated by Cyperaceae, which is consistently above 40%, with Poaceae much lower, at less than half that figure. Both tundra/ruderal and marsh/wetland herbs are much reduced, the latter to very low percentages, mainly represented by *Filipendula*, while the former maintains low values between 5 and 10%. All other pollen types are hardly present. Micro-charcoal percentages rise in the later part of the zone to a consistent 30%.

HdV-128 and *Closterium* are still major components of the NPP assemblage, with frequencies initially consistent at almost 20%, although declining late in the zone. The algal assemblage is more diverse, however, with *Gloeotrichia* (HdV-146) now present and becoming increasingly important in the upper zone, as is *Botryococcus*, with *Spirogyra* (HdV-130), *Mougeotia* (HdV-313) and *Tetraedron* (HdV-371) joining the assemblage. *Pediastrum* is consistently present, but in low frequencies. Peaks of Copepoda occur. Taxa that are marshland rather than open-water aquatic also occur, including *Gaeumannomyces* (HdV-126), *Clasterosporium caricinum* (HdV-25) and *Sordaria* (HdV-55A).

(4). Zone F69-d: 105 and 100 cm

Betula values fall sharply while most other taxa remain unchanged, except for Cyperaceae which rises to approach 80%, dominating the zone. Poaceae values decline significantly, while marsh/wetland herbs are almost absent. Micro-charcoal frequencies rise to almost 50%.

Although proportions of individual taxa fluctuate, the NPP assemblage constituents are very similar to those of the previous zone. *Clasterosporium caricinum* is more prominent and *Botryococcus* less so, but overall there is little change.

(5). Zone F69-e: 95, 90 and 85 cm

Betula frequencies recover but remain low, with other trees and shrubs, notably *Pinus*, *Juniperus* and *Salix*, consistently present in very low percentages and *Corylus*-type, *Ulmus* and *Quercus* appear. Cyperaceae decline but are still abundant, at approximately 40%, whereas Poaceae recovers to account for more than 30% of tlp. Tundra/ruderal herbs maintain their values, while marsh/wetland herbs increase significantly to more than 15%, mainly contributed by *Filipendula*. Both *Typha angustifolia* and *T. latifolia* occur in high values (>20%). Micro-charcoal frequencies remain high at 40%.

The NPP assemblage becomes much more diverse in this zone, and while aquatic/open water algae remain important, all decline late in the zone, with some taxa of that group fading from the assemblage, notably *Closterium* and *Botryococcus*. *Pediastrum* and *Mougeotia* values rise sharply, and there is the appearance and rise to high frequencies of new taxa,

including *Zygnema* (HdV-58), *Herpotrichiella* (HdV-22), HdV-206, HdV-306, and *Chaetomium* (HdV-7A).

(6). Zone F69-f: 83, 80, 75 and 70 cm

Betula percentages increase to approximately 40%, with *Salix* percentages also increasing, to approximately 10%. *Corylus*-type percentages rise steadily through the zone and *Juniperus* and *Pinus* are consistently present. There are sporadic records of *Quercus* and *Ulmus*. Total tree and shrub pollen percentages rise sharply from 20% to 65% of the total pollen sum. Cyperaceae and Poaceae percentages are both reduced, to approximately 30% and 20%, respectively. Tundra/ruderal herbs are almost absent, but marsh/wetland herbs maintain high values, reaching almost 20%. Frequencies of *Typha* sp. are greatly reduced, but *T. angustifolia* is still recorded and other aquatics, including *Menyanthes*, enter the record. A consistent low *Equisetum* curve occurs. Micro-charcoal values decline through the zone, to only 10%.

Many open water NPPs are no longer recorded, notably HdV-128, *Gloeotrichia*, *Spirogyra* and *Pediastrum*. Marsh/wetland taxa *Zygnema*, HdV-306, *Chaetomium*, and *Herpotrichiella* increase and HdV-708 enters the assemblage in high values. *Anthostomella fuegiana* (HdV-4A) is recorded for the first time.

(7). Zone F69-g: 65, 62, 60 and 55 cm

In this zone, *Betula* frequencies remain at approximately 40%, while *Pinus* and *Corylus* types are steady at 10%. *Quercus* and *Ulmus* increase but remain at low frequencies, *Salix* declines and *Juniperus* disappears. Cyperaceae and Poaceae percentages change little, together representing c. 35% of the total pollen sum. The diversity of the herb pollen assemblage decreases greatly, with tundra/ruderal herbs virtually absent and marsh/wetland frequencies very low. Aquatics and *Equisetum* are no longer recorded. Micro-charcoal values are low.

Types HdV-708, HdV-306, *Herpotrichiella*, *Chaetomium* and *Zygnema* percentages decline sharply, while *Anthostomella fuegiana*, *Sordaria* and *Clasterosporium caricinum* all increase. *Cercophora* (HdV-112) and *Coniochaeta* cf. *lignaria* (HdV-172) are important for the first time.

(8). Zone F69-h: 52, 50 and 45 cm.

Corylus-type dominates the assemblage of this final zone, at over 50% of tlp. *Betula* falls to 20% while the other tree and shrub types maintain their values. Cyperaceae and Poaceae percentages are low, together constituting approximately 20%, with few other herbs recorded. Micro-charcoal records are negligible.

NPP percentages are generally low in this final zone, with *Anthostomella fuegiana*, *Chaetomium*, *Gaeumannomyces* and *Zygnema* the only taxa showing significant frequencies. Many aquatic and marsh taxa are no longer recorded.

3.3.2. Dating, Hydrology and Environment of Deposition

Four dates are available from the Flasks 69 sequence, forming a good chronological series (Table 1; Figures 7 and 8). The earliest dates, from within the lower limnic unit, show that deposition commenced (Table 4) in the Lateglacial Interstadial [39,65,66], which is represented by PAZs F69-a to c. The later, stratigraphically higher dates show that the start of the Holocene can be located in PAZ F69-e, so that the clastic clay-silt of PAZ F69-d represents deposition during the severe cold of the Loch Lomond Stadial, cf. Greenland Stadial GS-1 [40,67], which terminates the Lateglacial sequence. The changes in stratigraphic units and fluctuations between clastic and organic deposits recorded in the Flasks 69 core indicate climate oscillations between colder and warmer climate during the transition from Lateglacial to Holocene interglacial conditions. The lithology is illustrated and described in Figure 8, which also interprets the stratigraphy in terms of environments of deposition. The presence of marls, gyttjas and detrital organic material in the sediment column points to deposition within a water body, which survey showed was of small size. There is little to confirm this in the Lateglacial pollen assemblage (Figure 6), where aquatics are almost absent, perhaps because of the cold water and low biological productivity, nor to suggest

the type of water body involved. The major peaks of *Typha*, particularly *T. latifolia*, and the rise of a suite of marsh and wetland herbs in PAZ F69-e, however, confirm the presence of open water, albeit undergoing rapid terrestrialisation in the early Holocene.

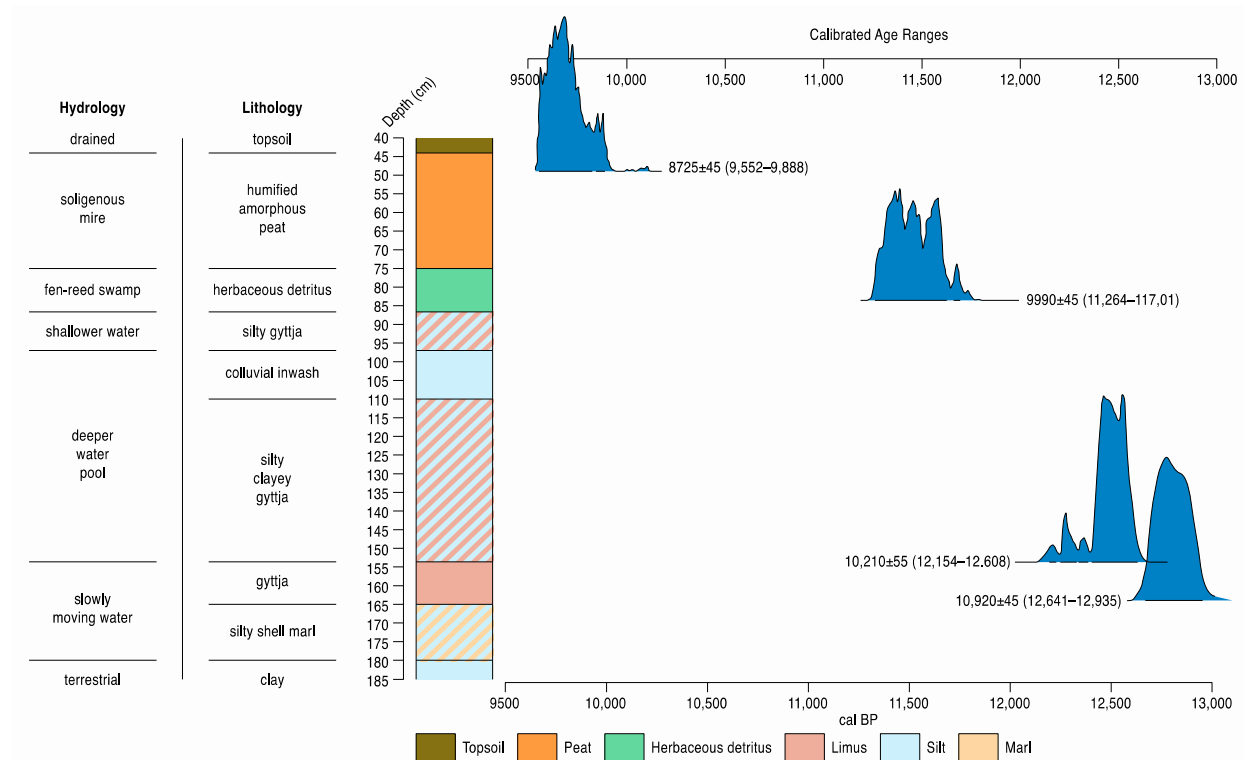


Figure 8. Conspectus of lithostratigraphy, chronology and hydrological history at Nosterfield the Flasks core 69. For lithology see Table 3. For dating details, see Table 1.

Table 4. Altitudes (m a.s.l.) of palaeochannels of the Ure between Marfield and Ripon South. Approximate ages are interpolated from radiocarbon or pollen data.

Site	Channel Altitude	Approximate Age cal. BP
Marfield Quarry	120	>13,850
Marfield Channel	100	13,850–13,500
Hackfall Gorge top	70	>13,000
Hackfall Gorge end	30	>13,000
Nosterfield Fan	40	13,000
Ripon North	27	5000–4500
Sharow Mires	17	4700–4200
Ripon South	16	4500–4000

While the pollen says little regarding the nature of the Flasks 69 water body in the Lateglacial, however, the NPP data have provided new insights. The presence of *Closterium* indicates cold open water [68] as does HdV-128, likely to be Volvocaceae algae [69], which prefers slowly moving, open water and is common in Lateglacial contexts [70,71]. This suggests that a shallow channel, rather than an enclosed pond, is a more plausible interpretation of the Flasks 69 feature, which was probably one of the many small, narrow palaeochannels that are visible across the Nosterfield fan on aerial photographs (Figure 5b). Excavated examples of these (Figure 5c) have displayed tripartite sediment fills similar to that recorded in the Flasks 69 profile. The rest of the Lateglacial Interstadial, before the cold phase of PAZ F69-d, still records open water, but the greater diversity of algae suggests a mesotrophic environment, more organic sedimentation and the start of the

colonisation of the channel fringes by shallow-water marsh plants, with *Clasterosporium caricinum* and *Gaeumannomyces* growing upon *Carex* species in those habitats [49,70,72]. *Carex* species were clearly very important in the Loch Lomond Stadial in both terrestrial and aquatic fringe environments, forming sedge-marsh communities. Pioneer algal taxa such as *Gloeotrichia*, *Tetraedron* and *Cosmarium* [68,71–73] are early colonisers that increase the trophic status of the water and improve conditions for later plant and algal hydrosere succession. Although still open, the rise in *Gloeotrichia* suggests that the water in the channel was clear and was becoming shallower from this stage onwards [74].

Holocene depositional environments (Figure 8) from PAZ F69-e onwards reflect continuing terrestrialisation of the channel, passing through shallow-water, reedswamp and fen stages, perhaps with some *Salix* carr, culminating in a soligenous mire. Marsh and wetland herbs characterize the earlier stages of this hydrosere, with *Equisetum* and *Typha*, and the NPP record matches this succession closely, with *Herpotrichiella*, *Mougeotia*, HdV-306, HdV-708, *Chaetomium* and *Zygnema* typical of shallow water mesotrophic reedswamp to fen environments [51,68,75–77]. *Pediastrum* colonies, preferring shallow, eutrophic water and warmer conditions [78,79] are common in this earlier transitional aquatic environment, although some *Pediastrum*, probably species tolerant of colder conditions [80], consistently occurred in low numbers throughout the cooler Lateglacial phases. The change to amorphous peat in the upper part of the profile (Figure 8) suggests full terrestrialisation of the channel surface and conversion to marshy soligenous mire communities, and the almost complete lack of fully aquatic taxa of any kind supports this. Records of *Anthostomella fuegiana*, *Sordaria* and *Coniochaeta* cf. *ligniaria* in the upper two PAZs indicate that the mire surface was occupied by grasses and sedges, perhaps including *Eriophorum*, indicating a more acidic peat [51], perhaps fringed with woody taxa.

3.3.3. Vegetation History

The tripartite stratigraphy comprising a limnic unit separated from a detrital and humified upper peat sequence by a thick clay layer suggests deposition during the Lateglacial period, with Interstadial organic lake muds laid down under temperate-climate conditions and covered by inorganic inwashed clay during the severe cold of the Lateglacial (Loch Lomond) Stadial, before deposition of peats in a renewed temperate, Holocene, climate. The pollen record shown in Figure 6 supports this, and agrees well with the radiocarbon dating, dates being close to the expected ages for the pollen features [81,82] that were selected for dating. Very open *Betula* and *Salix* woodland became established during deposition of the two organic units, but with considerable sedge- and grass-covered open ground. Sedge–tundra open herbaceous vegetation was dominant in the intervening cold phase, then climatic amelioration allowed increased biological productivity in the wetland and terrestrial plant succession at the start of the Holocene and the transition to a more wooded landscape. *Juniperus* scrub was shaded out by *Betula* woods, which were in turn replaced by *Corylus*, creating a closed canopy woodland ground cover.

3.4. Other Sites

This section briefly discusses dating and lithostratigraphy at sites around Ripon [18], at the downstream end of the Washland reach of the River Ure (Figure 1). Palynological data are not presented here, as the pollen record at these sites cannot be used for the relative dating of their basal deposits, other than all being post-*Ulmus*-decline [82,83] and so later than approximately 5000 ¹⁴C BP (c. 5800 cal. BP). This is too late in the Holocene for any diagnostic pollen assemblage change [82] that carries a chronological signature, other than the *terminus post quem* of 5000 ¹⁴C BP. Their ages of formation rely on radiocarbon dating of organic facies as low in the profile as possible, given the radiocarbon methodology constraints outlined in the methods section, so that their age determinations will be approximate. The lower lithologies of these three sites are shown in Figure 9, and are from an abandoned river channel at Sharow Mires (SH), and alluvial sequences at Ripon North (RN) and at a lower, short section at Ripon South (RS), the earliest at

that site. All three profiles rest upon sandy gravel. At Sharow Mires, five metres of silty organic sediment overlies the gravel and is capped by another five metres of silty clay, and represents a fluvial channel infill which silted up after abandonment. Ripon North is a quarry exposure, where an organic, silty, fine-grained alluvial palaeochannel infill rests upon fluvial terrace gravels. Ripon South is also a quarry exposure, where an alluvial channel fill comprising silty sandy sediments with silty organic layers overlies shelly sandy terrace gravel. The alluvial sediments exposed in an upper, later section at Ripon South are illustrated in Figure 10.

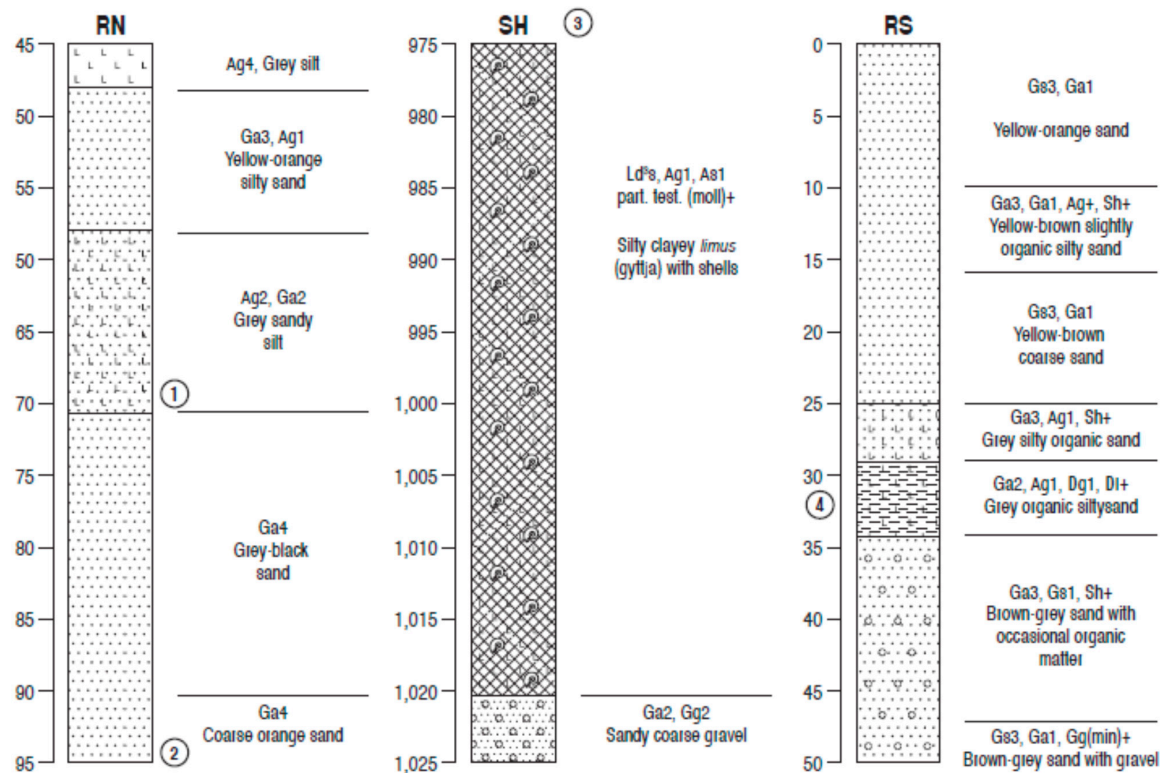


Figure 9. Lithostratigraphy and dating at the Ure sites around Ripon. RN is Ripon North Quarry, SH is the Sharow Mires abandoned channel and RS is Ripon South Quarry (short lower Section 2). Calibrated radiocarbon dates (Table 1) are (1) 2322 ± 165 (2) 3900 ± 50 (3) 4331 ± 95 (4) 4596 ± 185 . The Sharow Mires date is higher in the profile because of a lack of suitable terrestrial macrofossil material near the base. Stratigraphic notation and symbols follow Troels-Smith [57], with an English description. Earlier gravel extraction in the Ripon South Quarry, at Ripon Racecourse, exposed very early Holocene channel fill deposits [84].

Ripon North is furthest upstream (Figure 1) and the top of the basal gravel is at approximately 27 m a.s.l. The next site downstream is Sharow Mires, where the top of the basal gravel is at approximately 17 m a.s.l., whereas the altitude of the basal gravels at the most southerly site, Ripon South, is at approximately 16 m a.s.l. The estimated ages of the lowest dateable levels at Sharow Mires and Ripon South (Figure 9) are similar, although with wide calibrated age ranges (Table 1), and the base of the channel fill can be interpolated to between approximately 4200 and 4700 cal. BP. The age of the formation of Ripon North is more difficult to estimate, but is likely to be in the centuries after c.5800 cal. BP (post-*Ulmus* decline), and so earlier than the two downstream sites, as would be expected from its greater altitude; the relation of this group of sites within the terrace sequence of the Ure is illustrated in Figure 11. Although the dating of the formation of these three channels in the downstream reach of the washland Ure is very imprecise, they are clearly much later than channel formation in the Nosterfield and Marfield areas (Table 4). It is possible that the abandonment of river channels and renewed incision in the Ripon area between 4500 and

4000 cal. BP may be a response to climatic deterioration and increased rainfall, as recorded as wet shifts in bog profiles in northern England [85] during Holocene Event 3 and the transition to the Neoglacial in the North Atlantic region [86,87]. Increased anthropogenic forest clearance in the Pennines around Wensleydale at this time (the start of the Bronze Age) [88–91] could also have provided increased catchment water runoff, with climate change also encouraging river instability, flooding, incision, and channel alluviation at this time [92–94].



Figure 10. Illustration of the upper alluvial channel fill at Ripon South Section 1, a different and later section to that shown in Figure 9, showing layers of sands and silts, some of which are more organic. The tape is 2 m in length.

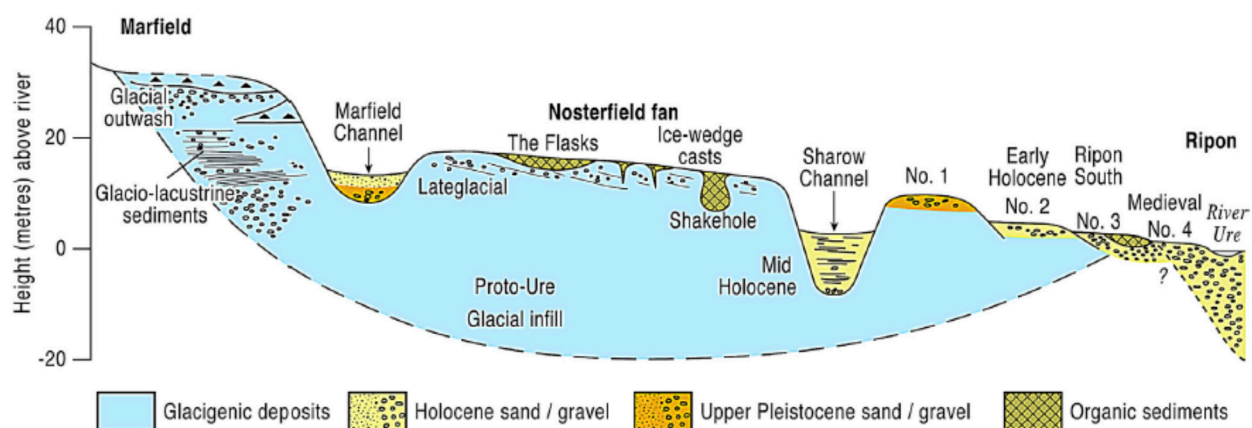


Figure 11. Schematic cross-section through the terrace sequences in the Ure valley, and the stratigraphic position of sites mentioned in this paper and shown in Figure 1. Note that the illustration of the infilled pre-glacial Proto-Ure valley is schematic. This pre-glacial channel was mapped by the Geological Survey and noted by Howard et al. [84] at their Ripon Racecourse site, which was an earlier version of our ‘Ripon South’, the latter located c. 0.5 km further to the SE and not overlying the buried valley, which does not follow exactly the same course as the modern river.

4. Discussion

4.1. Lateglacial and Early Holocene Vegetation History

The combined vegetation history from Marfield and the Flasks 69 is an important contribution to the Lateglacial and early Holocene vegetation history of Wensleydale and the North Yorkshire Pennines in general. It needs to be considered in some detail as the relative dating at Marfield depends upon it and the dating sequence at the Flasks 69 is confirmed by it. The pollen data from these two profiles are similar to the Lateglacial and early Holocene record from other sites in the local region, at Dishforth Bog [95], Bingley Bog [96], Bedale [97] and Tadcaster [98], and particularly the nearby sites within Snape Mires, only five km to the north and east [18,60]. The vegetation history at both Marfield and the Flasks 69 extends back to the temperate Lateglacial Interstadial, although the sequence at the latter site begins between 500 and 1000 years later, reflecting the relative ages of the two channel features. At both sites *Betula* frequencies are similar, at approximately 30% of tlp during the middle of this temperate climate phase. Open woodland, probably of a parkland type, was becoming established as temperatures recovered after the brief mid-Interstadial cold event (Greenland GI1-d) [40,99] at approximately 13,850 cal. BP, which is recorded at nearby Mill House [60], at Bingley Bog [96] and at Tadcaster [98]. The lack of a pollen signature of this cold event in the Marfield pollen diagram suggests that the date of the Marfield channel abandonment was probably after that date. The high *Juniperus* frequencies at Marfield are typical of the northern part of North Yorkshire, seen in all the local diagrams [81], and its absence at the Flasks 69 reflects the later date of the start of pollen deposition at that site, after the main *Juniperus* maximum was over. For the rest of the Lateglacial, the two diagrams conform to the general pattern of vegetation change, with the partially wooded conditions of the later part of the Interstadial, although the *Betula* woodland was much better developed at Marfield than at the Flasks 69. This was probably because of the more stable soil conditions at Marfield, and more akin to Mill House [60], soil profiles having had longer to become established at both these sites than on the surface of the more-recently deposited and less sheltered Nosterfield gravel fan. At all regional sites, this succession to woodland was interrupted by the severe cold of the Loch Lomond Stadial and vegetation reversion to a Poaceae- and Cyperaceae-dominated sedge-tundra, with Cyperaceae frequencies at both Mill House and the Flasks 69 reaching 80% of tlp, and *Artemisia* prominent.

Notable at all these sites are the high frequencies of micro-charcoal throughout the Lateglacial and particularly in the Loch Lomond Stadial. Upper Palaeolithic (Lateglacial) flints have been found in Wensleydale [100] as well as in Pennine caves [101], indicating that hunter-gatherers were present in these Pennine-flank valleys and in North Yorkshire generally during this period. It is possible that the microscopic charcoal particles originate from human burning of vegetation and from campfires. However, as the burning seems to have been ubiquitous, continuous and quite intensive, a natural origin is more likely, as the Lateglacial, and particularly the Loch Lomond Stadial, was climatically arid [39,40], and micro-charcoal frequencies fall sharply in the record from the early Holocene, when there were more people active in the area, but climate was wetter. Whatever the cause, these two sites are further examples of Lateglacial sequences rich in micro-charcoal, a widespread phenomenon [102]. The vegetation successions of the early Holocene are similar at both study sites, with tall herb communities followed by *Juniperus*, *Betula* and *Corylus*-type pollen maxima and the establishment of post-glacial woodland. The Marfield *Betula* peak reaches 80%, similar to those at Bingley Bog and Tadcaster, as full *Betula* woodland was established, although at the Flasks 69 it reached only half of that, probably due to continuing unstable soil conditions on the Nosterfield gravel fan. In contrast, the *Corylus*-type peak is pronounced at the Flasks 69, but less so at Marfield, being truncated by hiatus there, so that more stable soils had become established on the Nosterfield fan by then. Overall, the data from these two middle Ure pollen sites are representative of the early Holocene vegetation succession that is recorded at all the neighbouring North

Yorkshire pollen diagrams, with the radiocarbon dates at the Flasks 69 exactly as would be expected for these early Holocene vegetation changes [82].

4.2. Relict Fluvial Features—Terraces and Channels

The features that are most representative of the Ure system in its middle reaches are its highly complex series of relict terraces and channels. Many were carved by subglacial and ice-marginal meltwater during deglaciation [7] but others are evidence of course changes of the river and its tributary streams during the Lateglacial and Holocene, and of the processes driving terrace formation and fluvial channel abandonment. Such palaeochannels are a feature of all the river valleys of the eastern Pennines [103,104] and have been mapped in the Swale and the Wharfe as well as the Ure [18,34,105]. They occur in considerable numbers and formed at all stages of the Lateglacial and the Holocene, as rivers adjusted their courses in response to rapid incision due to isostatic (atectonic) uplift [106,107] and heavy sedimentation loads, particularly after major flood events caused by climate fluctuations and human impacts in the catchment [82,93,94,108]. This is well illustrated in the Ure drainage, with some relict river channels mapped at even higher altitudes, and therefore presumed to be older, than the Marfield channel, an example being the 5 km in length Thieves Gill feature [18,109] which lies at approximately 120 m above sea level, 20 metres higher than the High Mains sequence. Radiocarbon dating and palynology of as close to basal sediments as possible in these channels have provided in each case a *terminus ante quem* for their creation, probably by river avulsion. Combined with their altitude above sea level, this information has allowed a reconstruction of fluvial history, particularly terrace formation and incision, in the middle Ure valley, and an exemplar for fluvial research in deglaciated terrain.

4.3. Wider Comparisons

This multi-disciplinary investigation of the fluvial archives of the mid-altitude Ure valley provides a valuable case study of fluvial activity and environmental change since deglaciation in an upland river system, and the findings invite comparison with research in similar contexts elsewhere in the British Isles and beyond. The Ure results conform to the general paradigm of climate-controlled fluvial evolution [110,111] with initial paraglacial high-energy braided rivers dominated by gravel deposition, followed by sandur-type outwash sediment distribution and then entrenchment and terrace formation, before settling into floodplains with migrating river courses and channel abandonment [112–116]. Fluvial regimes and the pattern of sedimentation and erosion in the Ure are similar to those recorded in the foothills of the hills of northern England as a whole, where considerable previous research exists. Most analogous to the Ure research has been the study of lengthy reaches of the Ribble Valley and its tributaries, on the western side of the Pennines [117–119], which has also combined geomorphological mapping of glacial and fluvial features, geochronology and palaeoenvironmental analyses. Similar multi-discipline records occur in the valleys draining the northern uplands in the Isle of Man, where fluvial incision into valleys full of deglaciation gravels led to the formation of terraces and alluvial fans at valley mouths between 15,000 and 10,500 years ago [120,121]. The similar geomorphological and fluvial deglaciation histories in these uplands are a product of the high availability of mostly coarse-grained sediment and the adjustment of rivers to the new high-energy drainage regime. Holocene records from these other fluvial archives also correspond with the Ure evidence, in that little fluvial activity occurs in the mid-Holocene but renewed incision and alluviation occurs in the later Holocene (Table 4). Climatic factors are likely to be responsible for this similarity, with human destabilisation of catchments probably also an influence [82,90,122–124].

The suite of incisions, fills and palaeochannels that are present in the Ure valley, and in those of the other rivers of northern England mentioned above, are also characteristic of fluvial evolution in the river valleys of northern mainland Europe which experienced major climate shifts during the Lateglacial and transition to the Holocene. Syntheses of

data from long reaches of valley are necessary for understanding these fluvial systems, and have been accomplished in Poland in the Vistula and Warta [110,125], both much larger rivers than the Ure. In both cases braided channels existed during the Lateglacial and meandering channels in the Holocene, and many abandoned palaeochannels have been investigated using palynology and radiocarbon dating, with a full range of examples from the late LGM through to the very late Holocene. Long-term fluvial dynamics have also been studied in the valleys of several large German rivers [126], as well as the Maas in the Netherlands [125,127] and in Poland and Spain [128], and, again, fluvial sedimentary units have been shown to correlate closely with climate changes on a continent-wide scale. As with the Ure, fluvial activity decreased markedly in the mid-Holocene, with high levels of activity in the Lateglacial and the late Holocene. The landforms and sediments found in these large North European rivers are closely analogous to the evidence from the much smaller River Ure described in this paper, and show that the processes and drivers that have governed fluvial evolution since deglaciation have operated irrespective of spatial scale and river size.

5. Conclusions

This study of the middle Ure valley shows that a multi-disciplinary approach, combining field mapping with lithostratigraphic and palaeoenvironmental analyses, can be used to reconstruct an integrated fluvial history that explains the genesis and evolution of both landforms and sedimentary facies. Such integration of research techniques is a strategy that is likely to prove valuable in a wide range of research contexts and locations. Microfossil analyses of sedimentary infills, allied to radiocarbon dating, have provided detailed information regarding the ages and environments of deposition of an altitudinal staircase of terraces, interspersed with erosional features, and so provide an understanding of the rate of incision and distribution of river channels in a deglaciated landscape. This understanding allows the fluvial history to be linked to external forces, mainly tectonic/atectonic uplift, climatic or human activity, which have driven fluvial changes during periods of stability and instability in the river catchment. North Yorkshire has proved to be an ideal field laboratory for this methodology, with its combination of upland and lowland glaciation in the Devensian. Repeated ice advance and retreat across a relatively small area created a complex mosaic of surficial, glacially-derived sediments and landforms, upon which were imprinted a suite of ice-marginal erosional and depositional fluvial features, providing excellent examples of riverine processes in deglaciated terrain.

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